AIP | Journal of Renewable and Sustainable Energy
FREE ACCESS THROUGH 2013

Performance of molten salt solar power towers in Chile

G. Cáceres, N. Anrique, A. Girard, J. Degrève, J. Baeyens, and H. L. Zhang

Citation: Journal of Renewable and Sustainable Energy **5**, 053142 (2013); doi: 10.1063/1.4826883
View online: http://dx.doi.org/10.1063/1.4826883
View Table of Contents: http://scitation.aip.org/content/aip/journal/jrse/5/5?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **5**, 053142 (2013)

Performance of molten salt solar power towers in Chile

G. Cáceres,[1] N. Anrique,[1] A. Girard,[1] J. Degrève,[2] J. Baeyens,[3] and H. L. Zhang[2,a)]
[1]*Faculty of Engineering and Science, Universidad Adolfo Ibáñez, Santiago, Chile*
[2]*Department of Chemical Engineering, Chemical and Biochemical Process Technology and Control Section, Katholieke Universiteit Leuven, Heverlee, Belgium*
[3]*School of Engineering, University of Warwick, Coventry, United Kingdom*

(Received 2 April 2013; accepted 11 October 2013; published online 22 October 2013)

Chile is facing important challenges to develop its energy sector. Estimations demonstrate that in its electricity consumption Chile will grow at an annual rate of 4.6% until 2030, despite ongoing efficiency improvements. To satisfy this demand in a sustainable way, the national energy policy promotes the integration of novel and clean power generation into the national power mix, with special emphasis on concentrated solar power (CSP). The present paper assesses the development of solar-based electricity generation in Chile by CSP, achieved by a Solar Power Tower plant (SPT) using molten salt as heat carrier and store. Such SPTs can be installed at different locations in Chile, and connected to the main national grid. Results show that each SPT plant can generate around 76 GWh_{el} of net electricity, when considering solar irradiation as the sole energy source and at a 16% overall efficiency of the SPT process. For operation in a continuous mode, a hybrid configuration with integrated gas backup system increases the generating potential of each SPT to 135 GWh_{el}. A preliminary Levelized Energy Cost (LEC) calculation provides LEC values between 0.15 and 0.18 $/kWh, as function of the overall process efficiency and estimated investment cost. Chile's solar irradiation favors the implementation of SPT plants. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4826883]

I. INTRODUCTION

Estimations for the future show that the electricity consumption in Chile will grow at an annual rate of 4.6% until 2030, despite ongoing efficiency improvements by consumers [CNE, 2008; 2011a]. According to the 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC), renewable energy will help in reducing greenhouse gas (GHG) emissions [IPCC, 2007]. Between 1990 and 2009, CO_2 emissions in Chili increased by 109% [CNE, 2011a], far in an excess of the world's average increase (38%), and only exceeded by Korea (129%) among OECD countries. Although Chili participates in the Clean Development Mechanism (CDM) with several projects to reduce GHG emissions, it has currently no legally binding emission limit under the Kyoto Protocol. At the 2009 United Nations Climate Change Conference (also called Copenhagen Climate Summit 2009), Chili, however, announced its commitment to reduce by 20% its greenhouse gas emissions by the year 2020 [OECD, 2011]. As the carbon footprint will play a strategic role in the future, carbon emissions should be reduced using cleaner technologies and shifting towards renewable energy sources. This move is strengthened by the current value and depletion of traditional fossil fuel sources.

Considering the mentioned concerns, a sustainable development in the energy sector is imperative, and different sustainable energy matrices should be examined [CNE, 2008 and 2011b; IEA,2011a and 2011b; IEA,2009]. Among the sustainable energy sources, solar energy is one

[a)]Author to whom correspondence should be addressed. Electronic mail: Zhanghl.lily@gmail.com

attractive alternative, as it relies on an inexhaustible and import-independent resource, i.e., the sun [Ortega *et al.*, 2010; Zhang *et al.*, 2013]. Amongst solar energy technologies, Concentrated Solar Power (CSP) can provide renewable energy in regions with high levels of irradiation and clear skies, like northern Chile [Anrique, 2012; OECD/IEA, 2010]. Additionally, when this solar power technology is enhanced with thermal energy storage (TES) and backup systems (BS), it offers electricity that can be dispatched when required, enabling it to be used for peak, shoulder and even base loads [Zhang *et al.*, 2013].

II. ELECTRICAL BACKGROUND IN CHILE

In December 2011, Chili's main electrical grid, the Central Interconnected System (SIC), had a Non-Conventional Renewable Energy (NCRE) installed capacity of only 4.4%: from a total of 12 365.1 MW, only 549.9 MW are from NCRE plants (Figure 1). The second leading electrical grid, i.e., Northern Interconnected System (SING), located in the Atacama Desert, performed even poorer with a NCRE installed capacity ratio of barely 0.4%, representing 14.9 MW (capacity provided by 4 small run-off-river hydroelectric plants) within a total of 3963.8 MW installed capacity (Figure 2).

In contrast with other countries in South America, Chili knows high electricity prices, even when not considering subsidy distortions that exist in other countries. This difference in the electricity prices is mainly explained by the country's fossil fuel scarcity, making Chile a major net importer of energetic resources [CNE, 2011a].

Following a strong public disapproval, recent electricity generation projects by conventional technologies have been abruptly canceled or postponed, highlighting the population's negative perception towards conventional generation technologies and towards their environmental impact [CNE, 2011b]. These events also generated uncertainty in the electricity market, whilst creating a very favorable context towards new NCRE projects, with a focus on Concentrated Solar Power technology. To enhance the rate of development, it is necessary to provide novel insights and tools, together with an appropriate technical and economic analysis. Concentrated Solar Power technology has been widely investigated and applied in many countries [Zhang *et al.*, 2013; OECD/IEA, 2010], and these examples serve as a solid basis for promoting CSP technology within the Chilean context.

Chile is at a critical moment in its history. It is faced by the enormous challenge and the noble task of generating the right conditions to achieve development over the coming decades. This is the objective set by the Government and represents the serious aspiration of this country to bring greater and better opportunities for Chilean people. Between now and 2020, growth rates of around 6% to 7% are projected for electricity consumption in Chile, which means almost an extra 100 000 GWh of total electricity demand by that year, implying that an increase in supply of some 8000 MW of new generation projects will be needed to satisfy the demand. This is a mammoth undertaking, particularly considering that Chile is predominantly an

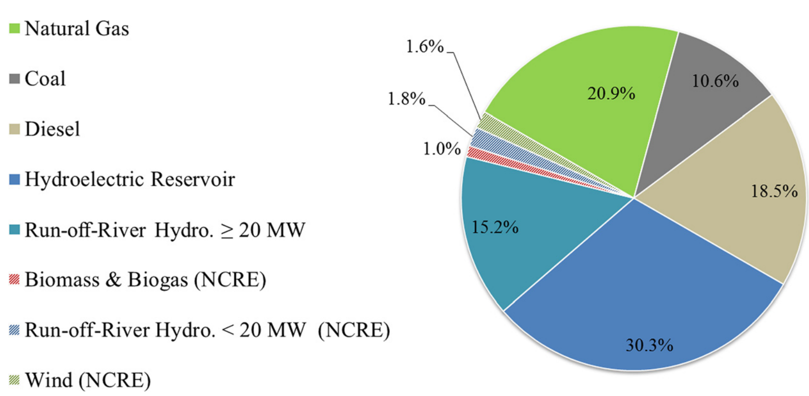

FIG. 1. Installed Capacity of SIC, December 2011 (12 365.1 MW) [CNE, 2011a].

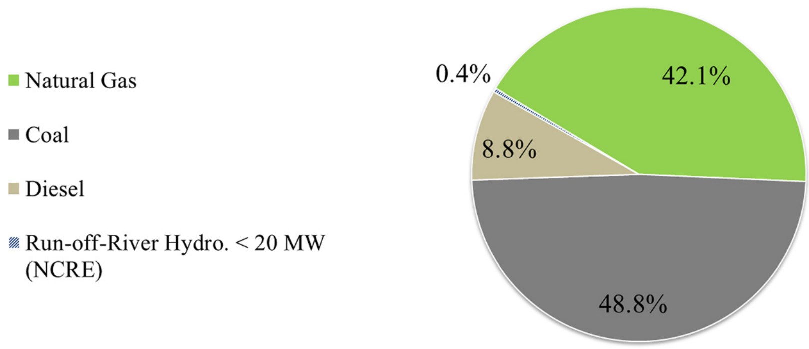

FIG. 2. Installed Capacity of SING, December 2011 (3963.8 MW) [CNE, 2011a].

importer of energy resources and that it has in recent years been particularly dependant on fossil fuels, whose price increases have increased the marginal costs of energy generation, leading to higher electricity prices from about 50 $/MWh in 2006 to about 120 $/MWh in 2012 for SING and between 150 and 200 $/MWh for SIC.

Looking to the long-term, Chile needs to move forward in creating the conditions for making the matrix ever-cleaner, more diverse and safer, in ensuring there is the greatest possible number of actors in each segment and that the networks are sufficiently robust and have enough slack. It is therefore essential to have a national strategy which holistically includes each of the elements necessary for achieving a clean, secure, and economical electricity matrix in the long-term. This is the commitment of the National Energy Strategy (NES). One of the laws to promote Non Conventional Renewable Energy sources, i.e., "Law 20.257" sets the target of 10% for NCRE by 2024. The Chilean Government regards this target as inadequate, and will hence perfect the current legislation, progressing in the design and implementation of alternative promotion mechanisms, as well as building Pilot Projects. With the measures defined in this strategy, Chile is looking to more than double this share of NCRE sources in the matrix during the next decade. Figure 3 illustrates how Chile shows significant potential in renewable resources, which can be exploited to generate electricity and heat. Within this scope, pilot plants of

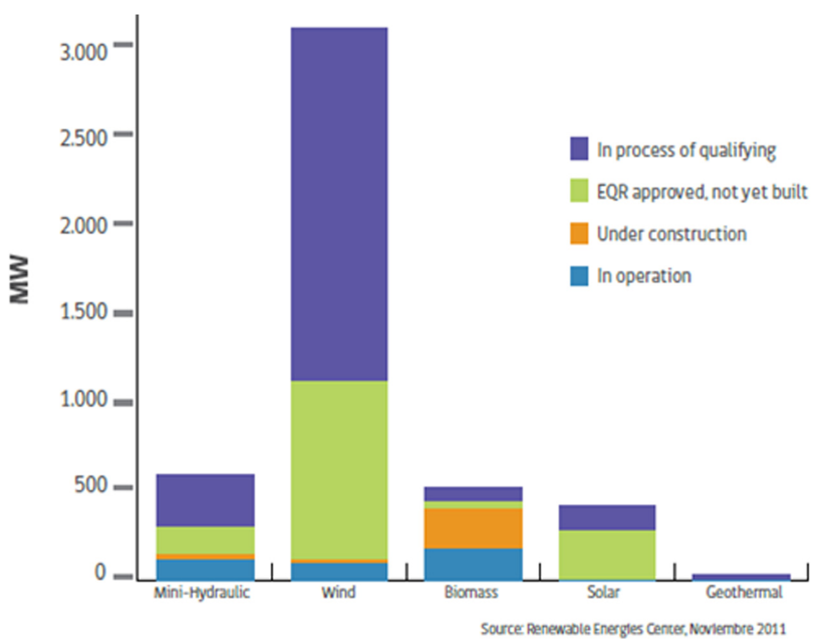

FIG. 3. State of NCRE projects by the end of 2011.

photovoltaic and geothermal nature are already being implemented. Hydropower, already responsible for about 30% of the electricity generation, will be further developed and major projects are programmed for the South of the country.

The use of NCRE presents economic and technical challenges that must be addressed without delay to stress the importance of these NCRE projects within the energy matrix. To achieve this goal, the following measures are presented in the National Energy Strategy:

(i) *Tender Mechanism to encourage the development of NCRE*: Parallel to the scheme included in the laws in this area, and with the goal of attracting investors interested in developing NCRE projects, open tenders will be carried out by NCRE block, in which the generators who participate could be awarded a State subsidy to improve the conditions of energy sales. This will be defined according to the bids submitted. This will decrease the risks to which such projects are currently exposed. Through this measure, they will support those new technologies that are not currently be sufficiently competitive to enable them to develop. This mechanism will complement current legislation.

(ii) *Geo-referenced platform—Economic potential for NCRE projects*: Public tools providing up-to-date information will be strengthened and implemented to guide and facilitate private investment in NCRE projects. A geo-referenced platform will be created that will compile dynamic information to assess the viability of a NCRE project. This will include a portfolio of NCRE projects; a database of potential resources and State land available for the development of such projects; the details of energy demand at an industrial, commercial, and residential level; information on roads and electricity infrastructure; environmental protection areas and available information on land planning so as to identify the availability of compatible lands with other productive uses. This platform will be integrated with the platforms of other State organizations that have the authority to manage national land, such as that of the National Assets Ministry and those available on the SEIA (Service of Studies of Environmental Impact). The goal will be to offer certainty regarding the feasibility of NCRE projects and to take greater advantage of public lands for energy development.

(iii) *Development and financing:* This line of action will focus on working with other public institutions to design and strengthen development mechanisms, consisting of the creation of effective coverage, insurance, new lines of credit with international financing, feasibility studies, among other economic incentive measures.

(iv) *New institutions to Boost NCRE*: As it is important and necessary that the Government establishes policies regarding NCRE and that these policies are implemented for the benefit of Chile, it is proposed to create a new public institutional structure to promote and facilitate the conditions for establishing non-conventional renewable energy in Chile, in addition to the current tasks of the Renewable Energy Center (Centro de Energías Renovables, CER).

(v) *Net metering for residential generators*: In order to consolidate the distribution of energy generated as an effective solution, tending towards a more efficient electricity system with increased supply, a regulatory design incorporating Net Metering will be implemented after approval by Congress. The objective of this initiative is to allow end users (e.g., families or small businesses) to install technologies for generating electricity from non-conventional renewable energy sources in their homes or businesses. The energy generated by each of these small producers may be used for own consumption or for injection into the network, to the point where they may even receive a net payment from the distributor for the electricity they deliver.

III. SOLAR IRRADIATION IN CHILE

Recent research [Anrique, 2012; Ortega *et al.*, 2010; Zhang *et al.*, 2013] regarding the potential of solar irradiation in northern Chile, points towards the Atacama Desert as being one of the most adequate regions worldwide for the development of CSP as the region presents a high number of clear skies during the year, due to the high aridity, with annual average precipitations below 50 millimeters per year [Mainguet, 1999]. The average irradiation in the north of

TABLE I. Solar irradiation in CSP plants and project locations [Zhang *et al.*, 2013; Larrain *et al.*, 2010].

CSP plants	Location	Radiation kWh/m^2-day
Plataforma solar almeria	Almeria, Spain	4.82
SEGS	California, USA	5.86
Abengoa ISCCS project	Ain-Ben-Mathar, Morocco	4.84
Gemasolar	Sevilla, Spain	5.75
No CSP plants	Atacama Desert, Chile	≈6

Chili is higher than in some places where CSP technologies are currently been used, as illustrated in Table I.

The present research considers solar irradiation data obtained from the National Solarimetric Archive (NSA) [CNE/PNUD/UTFSM, 2008], which is compiled from ground station measurements by the Universidad Técnica Federico Santa María (UTFSM). Figure 4 presents irradiation levels of the database used in this study and compared with satellite estimations [NASA, 2012].

The limited difference in NASA satellite predictions and ground measurements is due to the level of uncertainty of the not continuously operated ground stations. According to Pitz-Paal *et al.* (2007), a minimum of 8 years of data is needed to reduce the uncertainty level to below 5%. The present paper hence prefers the use of the NASA data.

For the evaluation of CSP plants, the present study considers the Atacama Desert (northern Chili), including six locations, possibly connected into the SING grid.

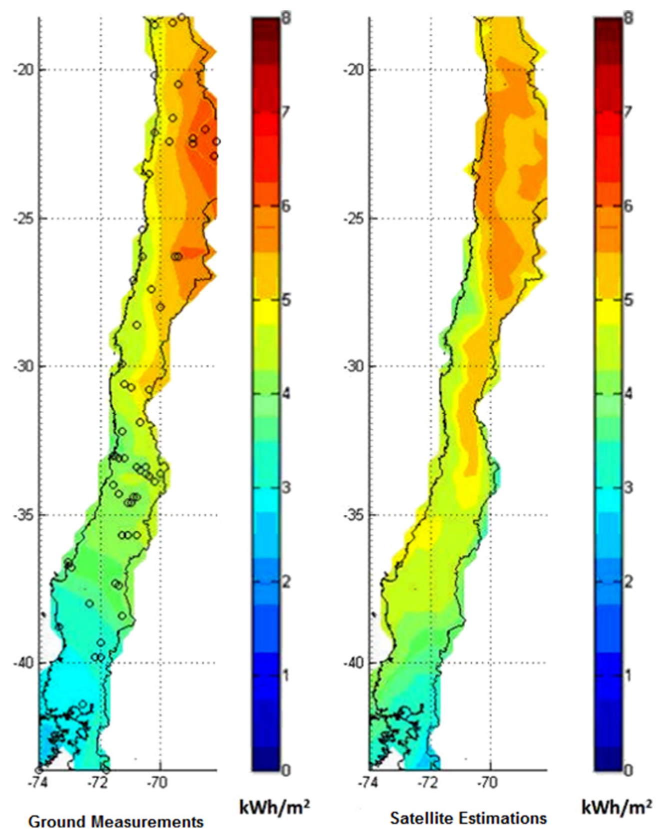

FIG. 4. Solar Energy Maps, Left: Ground Measurements [CNE/PNUD/UTFSM, 2008] (Circles are ground stations), Right: Satellite Estimation [NASA, 2012]. Daily solar radiation as annual average (kWh/m^2day).

The Calama area is moreover a very interesting location, and target for a first Solar Power Tower (SPT) plant, since its mining industry consumes a constant 25 to 30 MW throughout the year. This guaranteed consumption justifies the investment in a dedicated SPT plant.

IV. CONCENTRATED SOLAR POWER

CSP, also called Solar Thermal Power, is an electricity generation technology that uses heat provided by solar radiation, concentrated on a small area. Current technologies of Parabolic Trough Collector (PTC), SPT, Linear Fresnel Reflector (LFR), and Parabolic Dish Collector (PDC) were described in a previous reference [Zhang *et al.*, 2013]. The SPT technology is the second most installed concentrated solar power design behind PTC technology, and gradually sees its use increasing due to various advantages [Zhang *et al.*, 2013].

A PTC plant consists of a group of reflectors that are curved in one dimension in a parabolic shape to focus sunrays onto an absorber tube that is mounted in the focal line of the parabola. The reflectors and the absorber tubes move in tandem with the sun as it daily crosses the sky, from sunrise to sunset [Müller-Steinhagen and Trieb, 2004; Llorente *et al.*, 2011]. The group of parallel connected reflectors is called the Solar Field. Typically, thermal fluids are used as primary Heat Transfer Fluid (HTF), thereafter powering a secondary steam circuit and Rankine power cycle. Other configurations use molten salts as HTF and others use a Direct Steam Generation (DSG) system.

Solar Power Towers use a Heliostat Field Collector (HFC), which is a field of sun tracking reflectors, called heliostats, which reflect and concentrate the sunrays on a central receiver placed at the top of a fixed tower (Figure 5). Heliostats are flat or slightly concave mirrors that follow the sun in a two axis tracking. In the central receiver, heat is absorbed by a HTF, which then transfers the heat through exchangers to steam that drive a turbine in an advanced steam Rankine power cycle. Some commercial tower plants now in operation use DSG, using water as the working HTF [Müller-Steinhagen and Trieb, 2004]. Other plants use molten salts as HTF and storage medium [Zhang *et al.*, 2013]. Several towers can feed one power block.

Within the commercial CSP technologies, PTC plants are the most developed of all commercially operating plants [SolarPACES, 2006]. Table II compares both technologies on the basis of different parameters.

Water requirements are of high importance for those locations with water scarcity, e.g., in most of the deserts. As in other thermal power generation plants, CSP requires water for cooling and condensing processes, where requirements are relatively high: about 3000 l/MWh for PTC plants (similar to a nuclear reactor) compared to about 2000 l/MWh for a coal-fired power plant and only 800 l/MWh for combined-cycle natural gas power plant. SPT plants need less

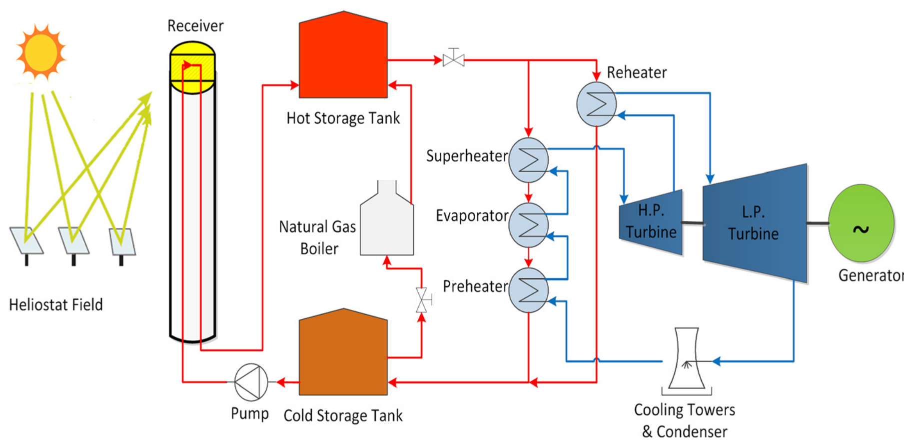

FIG. 5. Plant configuration. Red Line: Molten Salt Circuits, Blue Line: Water/Steam Circuit. Reprinted with permission from Torresol, available on http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en. Copyright 2012 Elsevier; Renewable Sustainable Energy Rev. **22**, 466–481 (2013). Copyright 2013 Elsevier.

TABLE II. Comparison between leading CSP technologies.

	Relative cost	Land occupancy	Cooling water (L/MWh)	Thermo-dynamic efficiency	Operating T range (°C)	Solar concentration ratio	Outlook for improvements
PTC	Low	Large	3000 or dry	Low	20–400	15–45	Limited
SPT	High	Medium	1500 or dry	High	300–565	150–1500	Very significant

water than PTC (1500 l/MWh). Dry cooling (with air) is an effective alternative as proven by the plants under construction in North Africa. However, it is more costly and reduces efficiencies. Dry cooling systems installed on PTC plants located in hot deserts, reduce annual electricity production by 7% and increase the cost of the produced electricity by about 10%. However, the efficiency reduction caused by dry cooling is lower for SPT than for PTC. The installation of hybrid wet and dry cooling systems reduces water consumption while minimizing the performance penalty. As water cooling is more effective, operators of hybrid systems tend to use only dry cooling in the winter when cooling needs are lower, then switch to combined wet and dry cooling during the summer.

A higher concentrating ratio of the sun, as applied in SPT, enables the possibility to reach higher working temperatures and better thermodynamic efficiencies. On SPT plants, the large amount of irradiation focused on a single receiver (200–1000 kW/m^2) minimizes heat losses, simplifies heat transport and reduces costs.

In terms of technology outlooks, SPT shows promising advances, with novel heat transfer fluids HTF being developed and achieving higher temperatures to improve the power cycle efficiencies. Moreover, higher efficiencies reduce the cooling water consumption, and higher temperatures can considerably reduce storage costs.

A tentative comparison of 50 MW$_{el}$ CSP plants with TES [Sargent and Lundy Consulting Group, 2003; Ortega *et al*., 2008] is presented in Table III. The capacity factor is defined as the ratio of the actual output over a year and its potential output if the plant had been operated at full nameplate capacity. Capacity factors of CSP-plants without storage and back-up systems are always low, due to the lacking power production after sunset and before sunrise.

A lower cost in SPT technology is mainly due to a lower thermal energy storage costs, which benefits from a larger temperature rise in the SPT compared to the PTC systems [Pitz-Paal, 2005a]. A higher annual capacity factor and efficiency in SPT is mainly possible due to the thermal storage, which enables a continuous and steady day-night output [Pitz-Paal, 2005b]. Additionally, in SPT plants, the whole piping system is concentrated in the central area of the plant, which reduces the size of the piping system, and consequently reduces energy losses, material costs and maintenance. Considering all mentioned aspects, SPT has several potential advantages.

Gemasolar is the newest commercial SPT plant in the world, as it began production in April 2011. It is the first commercially operating plant to apply molten salts as heat transfer fluid and storage medium. It is located on 185 hectares near Sevilla, Spain. The molten salt energy storage system is capable of providing 15 h of electricity production without sunlight,

TABLE III. Comparison for 50 MW$_{el}$ CSP plants with TES.

Parameters	PTC with oil, without storage and back-up	SPT with steam, without storage and back-up	SPT with molten salt, TES storage and back-up system
Mean gross efficiency (as % of direct radiation)	15.4	14.2	18.1
Mean net efficiency (%)	14	13.6	14
Specific power generation (kWh/m^2-yr)	308	258	375
Capacity factor (%)	23-50	24	Up to 75

TABLE IV. Gemasolar technical parameters [Torresol, 2012].

Characteristics	Gemasolar
Turbine net capacity	19.9 MW_{el}
Solar field area	304 750 m^2
Number of heliostats	2650
Heat transfer fluid	Molten salt
Receiver outlet temperature	565 °C
Backup fuel	Natural gas
Storage capacity	15 h (Molten salt), i.e., 15 × 50 MWh_{th}
Capacity factor	70%–75%

which enables the plant to provide electricity for 24 consecutive hours. Table IV shows the main characteristics of the Gemasolar SPT.

Although the turbine net capacity is 19.9 MW_{el}, it should however be remembered that the plant operation consumes part of the produced power, called the "parasitic." For the Gemasolar operation this amounts to about 1.1 MW_{el} (~0.95 MW_{el} in the molten salt circuit and ~0.15 MW_{el} in the power block). Taking these parasitics, and the capacity factor into account, the annual electricity supply to the grid is 110 GWh.

The six locations, selected from the NSA data, are given in Table V, with additional weather conditions given in Table VI.

The daily temperatures (minimum, maximum, average) of most of the locations are given by Tutiempo.

V. DESIGN APPROACH AND RESULTS

A. The solar irradiation calculation method, applied as example to the location of Calama

The underlying equations of the calculation method were presented in a previous paper [Zhang *et al.*, 2013]. The summary of the procedure is given in Table VII.

The essential steps of the calculations are illustrated for Calama, selected as representative location. Overall assessment results for all 6 locations will be presented in Sec. V B below.

The favourable solar irradiation position of Calama (and of all other locations) is already illustrated by the calculated high values of the average monthly clearness factor, $K_{T,av}$, as given in Figure 6.

The sequence of calculations follows the strategy presented by Zhang *et al.* [2013]. The daily total irradiation is thereafter obtained by applying the daily clearness index, K_T, and the daily extra-terrestrial irradiation H_0. The most important result towards CSP design requires the direct (beam) irradiation, obtained by withdrawing the diffuse irradiation, H_d, from the total irradiation, H. The resulting average monthly beam radiation, $H_{b,av}$, throughout the year, is shown in Figure 7.

TABLE V. Selected locations.

Locations	Nearest grid	Location name	Latitude	Longitude
Location 1	SING	Murmuntani	−18.37°	−69.51°
Location 2	SING	Pica	−20.5°	−69.31°
Location 3	SING	Parshall-2	−21.97°	−68.53°
Location 4	SING	Coya Sur	−22.39°	−69.61°
Location 5	SING	Calama	−22.46°	−68.91°
Location 6	SING	San Pedro de Atacama	−22.90°	−68.19°

TABLE VI. Weather conditions in the selected locations [Dirección Meteorológica de Chile, 2010].

Location	Altitude (m)	Annual average wind velocity (m/s)	Annual average T (°C)	Annual precipitation (mm)
Location 1	3964	3.17	7.32	…
Location 2	1435	3.99	8.49	…
Location 3	3316	4.15	9.27	1.0
Location 4	1110	4.01	15.19	1.0
Location 5	2294	4.15	12.3	1.0
Location 6	3400	4.43	4.22	1.0

Finally, a complete hourly evolution can be predicted by the calculations, as illustrated in Figure 8, where the radiation flux can be seen to increase from sunrise to noon, and thereafter decreasing again till sunset. It is also clear that the selection of the CSP nominal capacity will be a compromise between the seasons, accounting for the capability of thermal storage, and the use of a backup system.

B. Methodology to apply the predictions in CSP design, and results for Calama

Having established the annual, monthly and daily levels of direct (beam) solar irradiation, its impact on the power yield of the CSP can be assessed. To do so, it should be remembered that each of the operations of the overall CSP-layout has its own efficiency, reflected in the overall efficiency. The projected overall efficiency of CSP plants was assessed by Sargent & Lundy Consulting Group [Sargent and Lundy Consulting Group, 2003] and by Sandia National Laboratories (SNL) [Pacheco, 2002] as presented in Table VIII, including projected increased efficiencies as a result of present and future improvements.

The efficiencies of the essential components have been reported by S&L, and are represented in Table IX.

Considering that about 5% of the generated electricity will be used internally for the plant utilities (mostly pumping), 95% of the combined efficiencies does indeed vary between 15% and 18%.

The final CSP performance simulation follows the strategy of Figure 9, with a specific algorithm to be used, in terms of direct normal irradiance (DNI), thermal energy storage (TES), and backup system (BS), as previously presented by Zhang *et al.* [2013]

- DNI is calculated on hourly bases
- The total energy flux reflected by the heliostat field is calculated

TABLE VII. Sequence of calculation [Zhang *et al.*, 2013].

Known	The solar constant $G_{sc} = 1367\ W/m^2$
	The angle and distance of the sun vs. position on earth [f(latitude, time)]
	Satellite data of monthly average solar irradiation H
	Data on temperature, rainfall and wind speed…
	Day of the year, sunrise/sunset time
Sequence	(1) Calculate solar extraterrestrial irradiation, H_0
	Calculate average clearness index $K_{T,av}$
	Daily K_T
	Daily total irradiation $K_T \times H_0$
	(2) Use sequence of days (not needed with Hargreaves K_T)
	(3) Determine daily diffuse irradiation ratio H_d/H
	Predict hourly irradiation values: I/H, diffuse I_d/H, and direct (beam)$I_b = I\text{-}I_d$

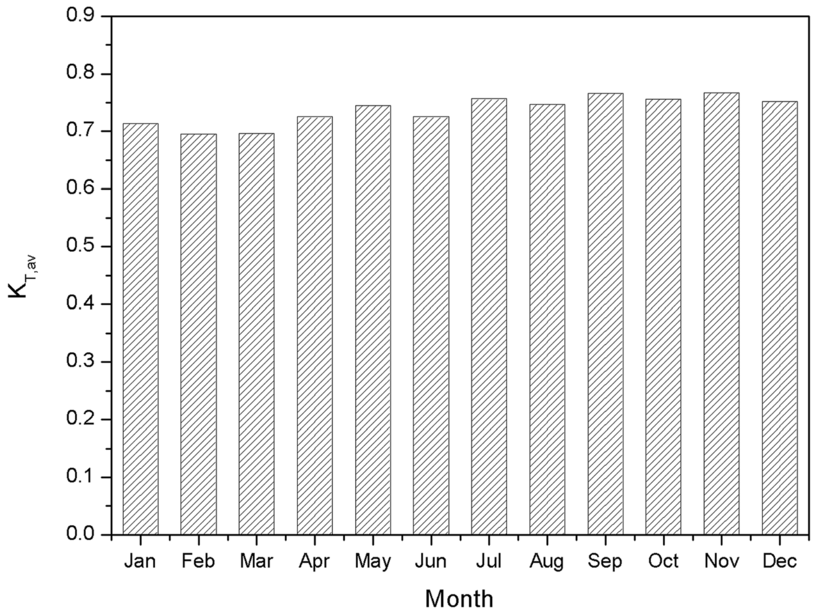

FIG. 6. Average monthly clearness factor, $K_{T,av}$, for the location of Calama.

- The expected nominal capacity of the plant is selected
- 21 consecutive days of lowest radiation levels are selected to coincide with the maintenance period, thus limiting losses during plant stand-still
- From a given starting day of the year, e.g., January 1st., at 6:00 a.m., and repeated for all hours of the year, the following different options need to be assessed:
  - if the solar thermal flux exceeds the required value to operate the plant at nominal capacity, only solar thermal energy will be used, whilst excess solar energy is stored in the HTF hot storage tank. The BS-system is not used, and additional excess solar thermal energy cannot be used;

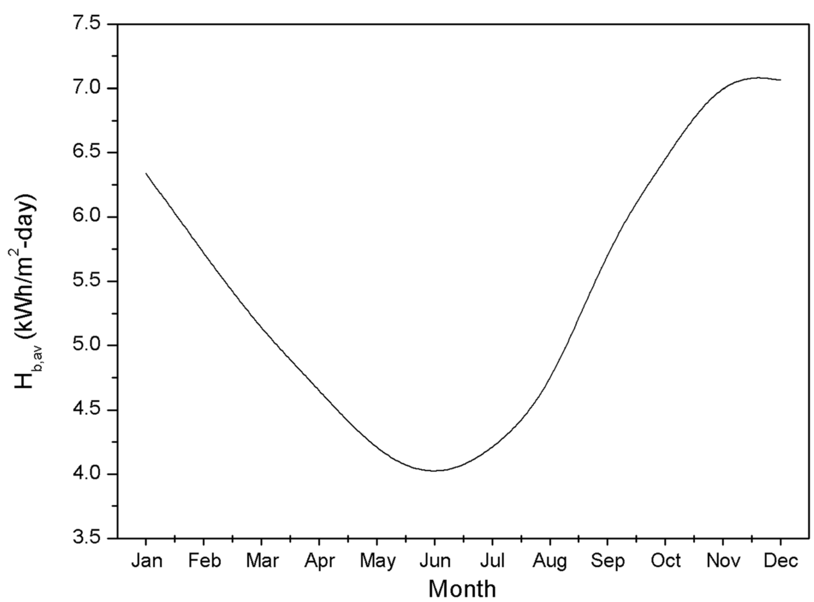

FIG. 7. Evolution of the average monthly direct (beam) irradiation in Calama.

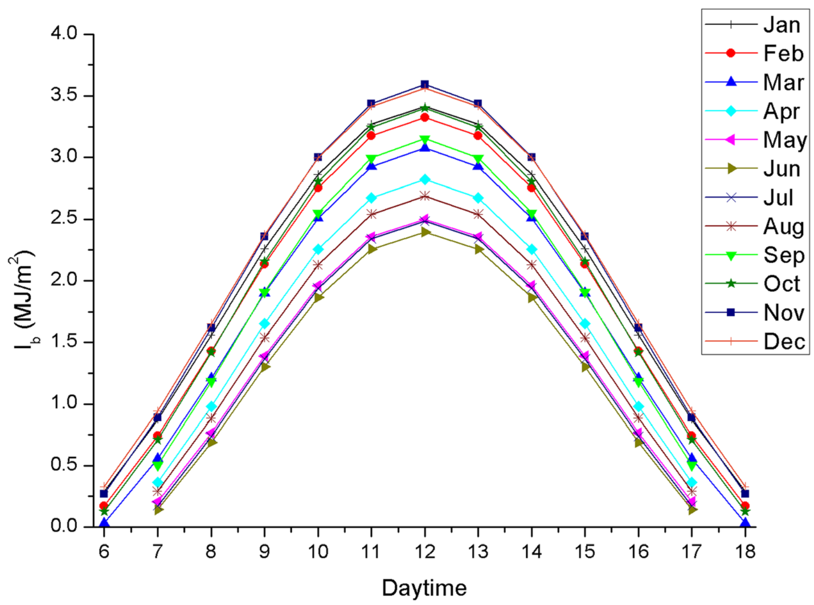

FIG. 8. Hourly evolution at the 15th of the respective months.

– if the solar thermal flux is insufficient to meet the nominal capacity, but enough thermal energy is stored in the hot tank, no BS is needed, and the plant will operate on combined solar radiation and stored energy;
– if the combined solar thermal flux and energy stored are insufficient, the plant needs to operate in its Hybrid Configuration, using the BS to meet the thermal requirements.

As output, the simulation provides for each location: electricity generation, hourly stored energy, and hourly backup requirements. Similar to the Torresol-Gemasolar project, the power plant capacity is 19.9 MW_{el} and the storage capacity is $\sim$800 MWh. Due to the higher solar irradiation characteristics in Calama against Sevilla (Table I), the total annual production capacity is set at 135 GWh/yr (against 110 GWh/year obtained at Gemasolar).

Results of the simulation for the Calama initiative, reveal that the sole solar generation will account for 76.7 GWh/yr, in the case of a conservative 16% overall efficiency, increasing to 86.3 GWh/yr at an overall efficiency of 18%. To reach an annual total of 135 GWh_{el}, the required average monthly back-up system varies inverse proportionally with the attained efficiency, and reaches its maximum, between 40% and 50% in the winter periods, as illustrated in Figure 10.

C. Comparison between the six different locations (at efficiency = 14%)

In the first configuration (solar resource alone) and with an overall efficiency of 16% only, the annual electricity generation outputs are between $\sim$67 and 77 GWh/yr (see Table X). Location 5 (Calama) reaches the highest electricity generation output into the SING electrical grid.

In the second (hybrid) configuration, a backup system is incorporated to generate the remaining thermal energy required in order to reach the nominal power output of the steam turbine in a continuous operation mode. In this configuration, electricity generation power is fixed

TABLE VIII. Projected overall CSP efficiency.

Year of projection	2004	2004	2008	2008	2020	2020
Annual overall CSP efficiency (%)	13.0	13.7	16.1	16.6	17.3	18.1
Source of estimation	S&L	SNL	S&L	SNL	S&L	SNL

TABLE IX. Values of SPT-component efficiencies.

Component	Efficiency (%)
Solar field	48–50
TES	>99
Power block	∼40

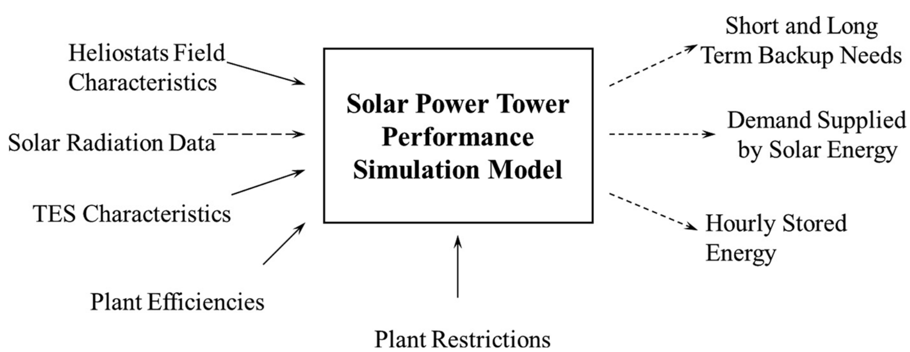

FIG. 9. Performance simulation method [Zhang *et al.*, 2013].

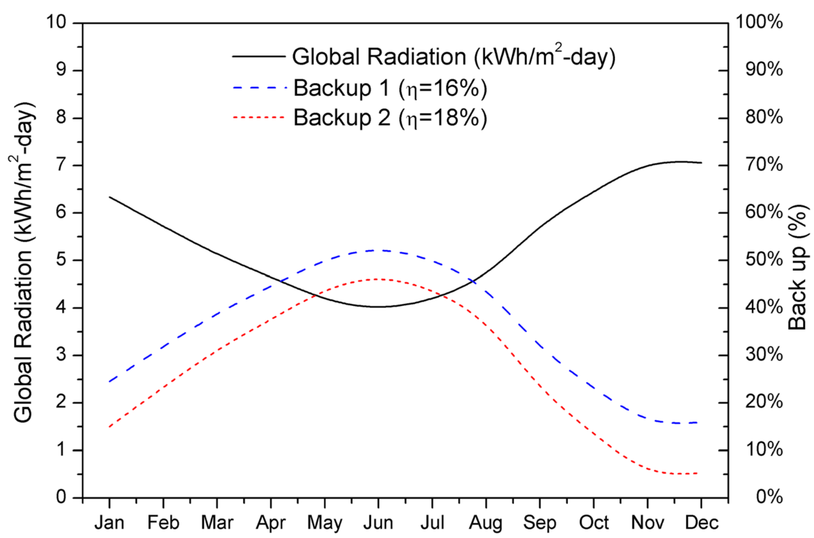

FIG. 10. Monthly backup requirements in the Calama SPT, in hybrid operating mode.

TABLE X. Annual electricity generation, solar resource alone configuration (16% overall efficiency).

			SING			
Location	Loc.1	Loc.2	Loc.3	Loc.4	Loc.5	Loc.6
Power (GWh/yr)	67.2	70.7	76.1	67.3	76.7	76.0

TABLE XI. Annual average backup requirements for each location, as % of 135 $GWh_{el.}$

SING					
Loc.1	Loc.2	Loc. 3	Loc. 4	Loc. 5	Loc. 6
50.2%	47.6%	43.6%	50.2%	43.2%	43.7%

at the nominal point, 19.9 MW_{el}. The total generated electricity is then 135 GWh_{el} per year, considering maintenance days (preventive and corrective) and energy losses. Table XI shows annual average backup requirements for each location, as percentage of total generated energy. Location 5 (Calama) again displays the lowest annual backup requirement.

The previous calculations were based upon an overall process efficiency of 16% only. SPT technology is looking forward to significant improvements in the following years; therefore, better results can be expected in the implementation of the technology in a short term period. For SPT with molten salt technology, improvements will occur in almost all components, however, major improvements are expected in the Receiver ($\boldsymbol{\eta_{receiver}}$) and in the Thermal Power Cycle ($\boldsymbol{\eta_{cycle}}$). It was already demonstrated for the Calama location (Sec. V B) that the solar contribution increases with increasing process efficiency, thus reducing the required back-up contribution. Of course, a similar impact is valid for the other 5 locations, proportional with the expected overall SPT efficiency.

A further demonstration of the SPT potential for northern Chili is provided by a preliminary Levelized Energy Cost (LEC) calculation. The LEC represents the generated electricity costs that include initial capital, return on investment and operating costs. LEC is widely used to compare competing energy sources and is normally expressed in US$/kWh.

The LEC is calculated as the ratio of Annualized Investment Cost (AIC, in US$) and the annual electricity generation (E_{an}, in kWh/yr):

$LEC = (\sum TICVC/\ (1+r)^t)/(\sum E_{an}/(1+r)^t)$
LEC, Levelized Energy Cost, as average lifetime levelized electricity generation cost
TICVC, The total of investment and variable costs of the complete process, including investment, operations and maintenance expenditures.
E_{an}, the annual electricity generation (in kWh/yr):
r, discount rate, taken at 6%
n, lifespan of the plant in years, taken as 20 yr (the normal period of guarantee provided, provided by the suppliers)
t, year under consideration, from 1 to n.

The total investment includes the costs of the solar field, of the TES, of the natural gas-fired backup system, of the cooling process (provided by sea water in the case of northern

TABLE XII. Values of economic parameters used in calculating LEC.

Parameter	Value
Solar field and power block	6 060 000 US$/MW [Damerau *et al.*, 2011]
Storage costs	1 110 000 US$/MW [Damerau *et al.*, 2011]
Backup costs	135 000 US$/MW [S&L, 2003]
Annual O & M costs	70 US$/kWh-year [Turchi *et al.*, 2010]
Natural gas	0.0164 US$/kWh [IEA, 2011b]
Discount rate (r)	6%
Life time of the plant (n)	20 yr
Land rental costs	305 US$/ha–month [CPN, 2009]
Annual costs for pumping 100 Mm^3/yr	vertical: 0.068 US$/$m^3$ per 100 m horizontal: 0.08 US$/$m^3$ per 100 km [Damerau *et al.* 2011]

Chile and, therefore, a function of the pumping distance and altitude to be reached). The variable costs include annual operation and maintenance costs, price of natural gas used in the backup system, land rental costs, pumping energy costs.

In the present assessment, economic factors from literature were used, as summarized in Table XII.

At an assumed pessimistic overall efficiency of 16%, and applying the parameter values into the equations ($TICVC = 145.10^6$ US\$), results in LEC-values between 0.175 US\$/kWh. An enhanced overall efficiency (16% to 18%) will reduce the LEC proportionally with the ratio of the assumed efficiency of 16% and the real efficiency. These LEC results are consistent with literature references for solar energy prices [Abengoa Solar, 2007; Cabello *et al.*, 2011; Kreith and Goswami, 2011, Fernandes *et al.*, 2012]. If moreover additional SPT improvements will reduce the expected value of the investments to about 100.10^6 US\$, the LEC-value will be reduced to 0.146 US\$/kWh.

Considering the current average marginal SING costs of about 0.12 US\$/kWh (against 0.15 to 0.20 US\$/kWh for the SIC grid), the economic potential of the northern Chili hybrid SPT projects is certainly significant.

VI. CONCLUSIONS

The simulation of a plant functioning without auxiliary system shows that a SPT in northern Chili can provide around 70 GWh_{el}/yr of net electricity to the electric grid. Considering the expected projections on technology improvements, by the year 2020, 86.3 GWh_{el}/yr should be generated in Calama, which is the best evaluated location. Adding a TES and backup system, the annual production can be increased to 135 GWh_{el}/year. The incorporation of a backup system contributes to the plant's reliability, enabling it to compete with other conventional plants in delivering energy in the intermediate or even base load schemes. The initial economic analysis at a low 16% overall efficiency, demonstrates that the LEC will vary between 0.15 and 0.18 US\$/kWh. With enhanced efficiencies (expected up to 18%), the LEC will be reduced significantly, and will only slightly be more expensive than the current SING cost and cheaper than the SIC cost. The results show that the solar conditions in the Atacama Desert of Chili are suitable for the implementation of a molten salt SPT.

ACKNOWLEDGMENTS

The work reported in the paper was part of the project CONICYT/FONDAP/15110019 (SERC–CHILE) and supported by the Center for the Innovation in Energy (UAI, Chile).

Abengoa-Solar, *Report Especial Diciembre 2007 Abengoa Solar*, 2007; available from http://abengoa.com/htmlsites/boletines/es/diciembre2007ext/electrica.htm.

Anrique, N., "Performance evaluation of a molten salt solar power tower in Chile," M.S. Thesis (Universidad Adolfo Ibánez, Santiago de Chile, Chile, 2012).

Cabello, J. M., Cejudo, J. M., Luque, M., Ruiz, F. Deb, K., and Tewari, R., "Optimization of the size of a solar thermal electricity plant by means of generic algorithms," Renewable Energy **36**(11), 3146–3153 (2011).

CNE, Comisión Nacional de Energia, *National Energy Balance 2011* (2011a); available from www.cne.cl.

CNE, Comisión Nacional de Energia (CNE), *Política Energética Nuevos Lineamientos: Transformando la crisis energética en una oportunidad*, 2008; available from: www.cne.cl.

CNE, Comisión Nacional de Energia (CNE), *Antecedentes sobre la matriz energética en Chile y sus desafíos para el futuro*, (2011b).

CNE/PNUD/UTFSM, *Irradiancia Solar en Territorios de la República de Chile*, 2008.

CPN, Cuentas Publicaas Nacionales, Ministerio de Buenes Nacionales; available at http://www.bienesnacionales.cl/planificacion-y-prersopuesto/cuentas-publicas/, 2009.

Damerau, K., Williges, K., Patt A. G., and Gauche, P., "Costs of reducing water use of concentrated solar power to sustainable levels: Scenarios for North Africa," Energy Policy **39**, 4391–4398 (2011).

Dirección Meteorológica de Chile, *Anuario Climatológico*, 2010.

Fernandes, D., Pitié, F., Cáceres, G., and Baeyens, J., "Thermal energy storage how previous findings determine current research priorities," Energy **39**(1), 246–257 (2012).

International Energy Agency, *Solar Energy Perspectives, Renewable Energy* (IEA, 2011a).

International Energy Agency, *World Energy Outlook* (IEA, 2011b).

International Energy Agency, *Chile Energy Policy Review* (IEA, 2009).

IPCC, *Climate change* 2007: Synthesis report, 2007.

Kreith, F., and Goswami, D. Y., *Principles of Sustainable and Renewable Energy*, 1st ed. (CRC Press, 2011).

Larrain, T., Escobar, R., and Vergara, J., "Performance model to assist solar thermal power plant siting in northern Chile based on backup fuel consumption," Renewable Energy **35**(8), 1632–1643 (2010).

Llorente, I., Álvarez, J. L., and Blanco, D., "Performance model for parabolic trough solar thermal power with thermal storage: Comparison to operating plant data," Solar Energy **85**, 2443–2460 (2011).

Mainguet, M., *Aridity: Droughts And Human Development* (Springer, Berlin, 1999).

Müller-Steinhagen, H. and Trieb, F. "Concentrated solar power," in *Quarterly of the Royal Academy of Engineering* (Ingenia, 2004).

NASA, *Satelite estimates of solar irradiation*; available on http://eosweb.larc.nasa.gov/cgi-n/sse/retscreen.cgi?email=-rets@nrcan.gc.ca, 2012.

OECD/IEA, *Technology Roadmap, Concentrating Solar Power*, 2010.

OECD, *Maintaining momentum, OECD Perspectives on Policy Challneges in Chile*, 2011.

Ortega, A., Escobar, R., Colle, S., and De Abreu, S. L., "The state of solar energy resource assessment in Chile," Renewable Energy **35**(11), 2514–2524 (2010).

Ortega, J., Burgaleta, J., and Téllex, F., "Central receiver system solar power plant using molten salt as heat transfer fluid," J. Sol. Energy Eng. **130**, 024501 (2008).

Pacheco, J., *Final Test and Evaluation Results from the Solar Two Project*, Sandia National Laboratories, 2002.

Pitz-Paal, R., Dersch, J., Milow, B., Téllez, F., Ferriere, A., Langnickel, U., Steinfeld, A., Karni, J., Zarza, E., and Popel, O., "Development steps for concentrating solar power technologies with maximum impact on cost reduction" (2005a); available at: http://pre.ethz.ch/publications/journals/full/j138.pdf.

Pitz-Paal, R., Dersch, J., Milow, B., Romero, M., Téllez, F., Ferriere, A., Langnickel, U., Steinfeld, A., Karni, J., Zarza, E., and Popel, O., *European Concentrated Solar Thermal Road-Mapping-Executive Summary*, Contract No. SES6-CT-2003-502578 (CEECOSTAR, 2005b), p. 144.

Pitz-Paal, R., Geuder, N., Hoyer-Klick, C., and Schillings, C., *How to get bankable meteo data*, NREL 2007; available from http://www.nrel.gov/csp/troughnet/wkshp2007.html.

Sargent and Lundy Consulting Group, "*Assessment of parabolic trough and power tower solar technology cost and performance forecasts*," National Renewable Energy Laboratory, 2003.

See http://www.tutiempo.net/en/ for Tutiempo.

SolarPACES, Annual Reports, 2006, 2007, 2008, 2009, 2010; downloadable from: http://www.solarpaces.org/Library/AnnualReports/annualreports.htm.

Torresol; available on http://www.torresolenergy.com/TORRESOL/gemasolar-plant/en, 2012.

Turchi, C., Mehos, M. Ho, C., and Kolb, G. Current and future costs for parabolic trough and power tower systems in the US market, 2010.

Zhang, H. L., Baeyens, J., Degrève, J., and Cacères G., "Concentrated solar power plants: Review and design methodology," Renewable Sustainable Energy Rev. **22**, 466–481 (2013).